碩士學位論文

중계기 기반 은닉 통신에서의 탐지 오류 확률 최대화

Worst-Case Detection Error Probability Maximization for Relay-Based Covert Communications

國立한밭大學校 소프트웨어융합大學院

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2024년 08월

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**List of Abbreviations**

|  |  |  |
| --- | --- | --- |
|  | **V2V** | **V**ehicle-to-**V**ehicle |
|  | **IIoT**  **MIoT** | **I**ndustrial **I**nternet **o**f **T**hings  **M**obile **I**nternet **o**f **T**hings |
|  | **PLS** | **P**hysical **L**ayer **S**ecurity |
|  | **MACs**  **TLS**  **5G**  **6G**  **DF**  **AF**  **DEP**  **LPD**  **FA**  **MD**  **QoF** | **M**essage **A**uthentication **C**odes  **T**ransport **L**ayer **S**ecurity  **F**ifth **G**eneration  **S**ixth **G**eneration  **D**ecode-and-**F**orward.  **A**mplify-and-**F**orward.  **D**etection **E**rror **P**robability  **L**ow **P**robability of **D**etection  **F**alse **A**larm  **M**issed **D**etection  **Q**uality **o**f **S**ervice |
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**Abstract**

Worst-Case Detection Error Probability Maximization for Relay-Based Covert Communications

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Advisor: Jihwan Moon

In this thesis, we find out the maximum detection error probability (DEP) across varying relay system types, specifically decode-and-forward (DF) and amplify-and-forward (AF). In our analysis, we consider a scenario where a transmitter sends both public and covert messages to a receiver through a relay, while the warden attempts to uncover covert messages. Considering the relay’s minimum DEP, we strategically allocate power between the public and covert messages to gain the highest possible DEP. This optimization process involves balancing the transmission power between the public and covert messages, aiming for maximum DEP.

We further analysis a delay-conscious comparison between DF and AF relay systems, utilizing the derived closed-form covert rates. In our analysis, we include various system parameters such as source and relay transmit power, noise uncertainty bound, and minimum required quality of service for both public and covert messages, leading to different performance dynamics between DF and AF. Finally, numerical results are utilized to assess the influence of system parameters on DEP performance.

Introduction is too short. Introduction should be longer than background.

**Chapter 1**

**Introduction**

This chapter gives the background information for the research presented in this thesis.

The thesis framework is discussed in the later portion of this chapter.

**1.1 Background**

Most of the recent advancements in wireless communication have evolved, which makes it easier in every aspect of human life. Applications of advanced technologies such as earth observation satellites, vehicle-to-vehicle (V2V), and industrial IoT (IIoT) [1].

Wireless communications are also become more dangerous in a number of ways. Security is crucial for mitigating these threats, encompassing areas such as cryptography, network security, and physical layer security [2].

Physical layer security is a method of securing wireless communication by exploiting the unique characteristics of the physical channel through which the communication occurs. Physical layer security focuses on the inherent properties of the communication channel itself to prevent unauthorized access and eavesdropping [3]. However, this physical layer security has some weaknesses; one aspect is its tendency to introduce complexity and overhead. The increased complexity may impact system performance and power consumption [1].

If I consider though background as an introduction of thesis, it looks like less professional. More precisely it seems to me a presentation slide. Very less discussion even though there is more to say about covert communication and importance of covert communication as well as physical layer security.

Recently, more sensitive topics include the fact that wardens are now able to take vital information using channels, in which information is sent from sender to receiver with hidden techniques such as encryption and physical layer security cannot hide transmission behavior [4], [5]. Hence, the use of covert communication or low probability of detection (LPD) can effectively protect information from adversaries [1]. The authors discussed in [4] how by exploiting the unpredictable noise surrounding the warden's receiver, the covert communication transmitter can adjust its transmission power effectively to evade warden detection, while ensuring accurate decoding by the legitimate receiver.

Using both finite and unbounded noise uncertainty designs, the researcher in [6] looked for covert communication, focusing particular attention to circumstances where the covert rate rises. Then, the researcher in [7] investigated how a transmitter can successfully convey covert messages to a receiver, achieving a positive covert rate by leveraging relay and multi-channel uncertainty.

Many curious researchers are now exploring relay strategies to examine covert communication. The comparison between DF and AF relaying strategies is conducted in [8], utilizing their achievable covertness quality of service. In this research, initially, equal power is distributed to each relay system. It is observed that in covert communication, DF relay outperforms AF relay. The strategy of DF and AF relay systems is such that DF relay decodes the signal first and then forwards it. In contrast, AF relay amplifies both information and noise signals.

The main objectives of fifth generation (5G) and sixth generation (6G) networks are to improve internet communication and ensure strong user information security. The number of Mobile Internet of Things (MIoT) devices has increased dramatically for both 5G and the soon-to-be 6G networks to handle risks posed to MIoT users. Although message authentication codes (MACs) and transport layer security (TLS) are two examples of enhanced encryption algorithms that 5G networks typically use to protect user data from interception and eavesdropping, a DF relay system may also be included in the security architecture of 5G or 6G networks.

**1.2 Contributions**

In this thesis, we find out the maximum detection error probability (DEP) across varying relay system types, specifically decode-and-forward (DF) and amplify-and-forward (AF). In our analysis, we consider a scenario where a transmitter sends both public and covert messages to a receiver through a relay, while the warden attempts to uncover covert messages. Considering the relay’s minimum DEP, we strategically allocate power between the public and covert messages to gain the highest possible DEP. This optimization process involves balancing the transmission power between the public and covert messages, aiming for maximum DEP.

We further analysis a delay-conscious comparison between DF and AF relay systems, utilizing the derived closed-form covert rates. In our analysis, we include various system parameters such as source and relay transmit power, noise uncertainty bound, and minimum required quality of service for both public and covert messages, leading to different performance dynamics between DF and AF. Finally, numerical results are utilized to assess the influence of system parameters on DEP performance.

**Chapter 2**

**System Model**

The considered scenario is illustrated in Figure-2.1. A transmitting node (S) sends both public and covert messages to a receiving node (D) through the relay (R). A detector notices the conditions silently and tries to detect any covert message presence. Additionally, we presume the existence of a sufficiently long shared secret between S, D, and R. Therefore, D and R know when S is transmitting messages [7].

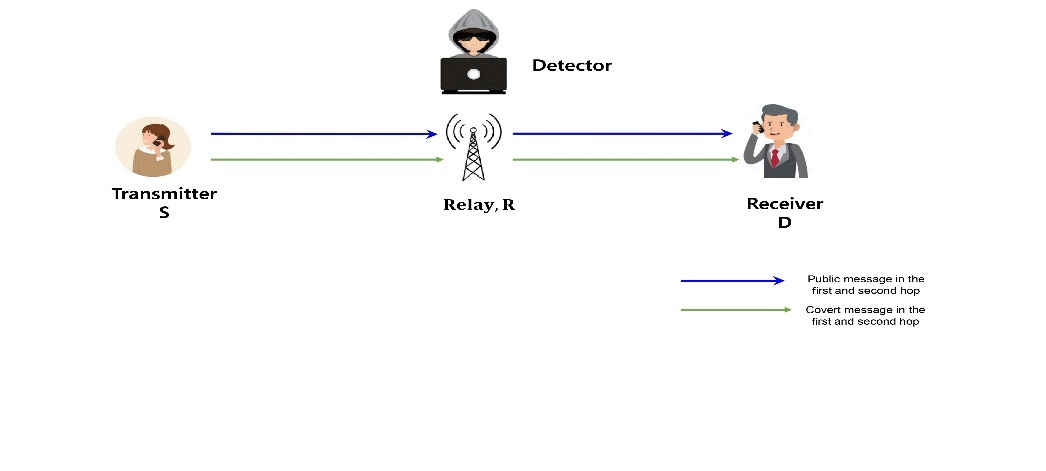


Figure 2.1: System model

**2.1 Received Signals**

The received signal at the relay is written as

(1)

Here in [1], and represent the public and covert messages from the transmitting node, respectively. Where denotes a complex Gaussian distribution with mean 0 and variance 1. The term means the source transmit power, The variables and denote the transmit power of public messages and covert messages , respectively. represents the additive noise. In this study, we consider that the noise varies uncertainly such that () in decibel range. Here, and stand for the mean and bounded range, respectively. We proceed by examining two distinct relay types, namely DF and AF, and subsequently derive expressions for both the public and covert rates at the destination node.

**2.1.1 DF relay**

Initially, we observe from equation (1) that the achievable rate for the combined message in the transmitting node (S)-to-relay node (R) hope is denoted by.

(2)

After successful decoding by the DF relay, the signal is forwarded to the receiving node, where the received signal can be represented as follows.

(3)

Where is the relay transmitting power. The achievable rate for the combined message in the relay node(R)-to-receiving node (D) hope is denoted by

(4)

From equations (2) and (4), it is apparent that the effective data rate for is bounded above by and for successful decoding at both the relay and receiving nodes.

Initially, the receiving node decodes the public message by treating the covert message as interference in [1], after that the achievable public message rate is as follows.

(5)

Secondly, the receiving node decodes the covert message by considering the public message as interference. As a result, we are achieving the covert message rate.

(6)

It is clearly proved that the actual public and covert message are limited by and , respectively.

**2.1.2 AF relay**

The AF relay transmits to the receiving node, which receives it as an amplified version of .

(7)

In here, denotes the normalized unit-power signal from the AF relay.

We can set achievable rates for the public and covert messages as (5) and (6), respectively.

(8)

(9)

Where

**2.2 Detection Performance at the Warden**

Regarding the detection of covert communication, the warden will try to find any hidden messages. To find out if the public messages contain any concealed messages, an algorithm will be used. An algorithm will be developed as the signal’s effective remainder considering that the relay perfectly knows and [1]. We do two hypothesis tests on its observations as

(10)

In this case, indicates that no covert message was sent by the transmitting node, while indicates that a covert message is present. We assume that warden uses a radiometer to detect the signals, and that after gathering number of ample signals. The detector can apply test statistic as

(11)

Two kinds of detection errors are typically introduced by the hypothesis test. The first kind of error is called a false alarm (FA), when transmitting and receiving nodes are in communication but the warden is unable to notice it. Missed detection (MD) errors are the second kind of error when the warden incorrectly determines that transmitting and receiving nodes are in communication even if there is no real communication between the transceivers. Thus, the detection error probability (DEP), denoted as , is made up in [1] as

(12)

When for a given threshold , the warden determines that a covert link is present. Where and denote the probabilities of false alarm and missed detection, respectively. According to [1], the warden assumes that the covert trasnmission happens randomly, meaning that .The optimal minimizing the DEP can achieve as

(13)

And [1] also provides the corresponding minimal DEP

(14)

as long as . If the warden knows the exact value of , then (13) produces the worst-case minimum DEP.

**Chapter 3**

**Problem Formulation**

In this section, we aim to measure the DEP performance between DF and AF relay systems. We initially need to determine the optimal power allocation between public and covert messages that maximizes the DEP. We then formulate our optimization problems in the below, depending on the DF and AF relay.

**3.1 DF relay**

In the DF relay scheme, the optimization problem can be given by

(P1): (15a)

subject to  (15b)

(15c)

(15d)

(15e)

(15f)

(15g)

(15h)

Where the actual rates for the public and covert messages are indicated by and , respectively. In (15b) and (15f), we set the minimum quality of service on and on in order to maximize the DEP. The upper constraints on and in (15c)-(15e) that were discussed in section 2.1.1. By setting the noise variance at DF relay, we consider the lowest feasible . Constraint (15g) ensures a positive minimum DEP, and (15h) sets a feasible region for

**3.2 AF relay**

The optimization problem for the AF relay method can be expressed as

(P2): (16a)

subject to (16b)

(16c)

(16d)

(16e)

By detemining the noise variance at AF relay, we impose the minimum quality of service and on the upper bounds and in (16b) and (16c) in order to maximize the DEP. The constraints (16d) and (16e) correspond to (P1).

**Chapter 4**

**Proposed Solutions**

We provide the optimal solutions to the optimization problems (P1) and (P2).

**4.1 DF relay**

In this subsection, we consider the minimum quality of service denoted for public messages, which must adhere to condition . Constraint(15g) can be rewritten by

(17)

Therefore, constraints (15g) and (15h) are decreased to using

(18)

We also observe that in (15c) and in (15d) have larger feasible regions when is reduced. Hence, we can just set the optimal to the minimum required rate from (15b), (19)

Without losing optimal performance.

(P1) is reformulated into

(P1.1) (20a)

subject to (20b)

(20d)

(20d)

(20e)

Where constraint(20b) comes from the combination of (15c) and (15e), and (20d) is a re-expression of (15d). Hence, (20d) and (20e) constraints can be expressed in terms of

(21)

Importance, notice that (P1.1) shows that in order to guarantee the feasibility, the minimum level of quality of covert rate must fulfill the condition . Furthermore, we note that when is declined, the feasible region for on the right-hand side in (20b) is larger. Consequently, it is important to remember that the optimal achievable covert rate is from (20d).

(P1.1) is restructured as

(P1.2)  (21a)

subject to (21b)

(21c)

Observing the upper limit of on the right-hand side in (21b), we can conclude that that the optimal should be as high as possible.

(22)

**4.2 AF relay**

The optimal solution for (P2) can be found as

In this subsection, we consider an equivalent minimum quality of service and for the public and covert message, respectively, as previously discussed in the DF relay system. From constraints (16d) and (16e), we derive the same value of that we obtained from constraints (15g) and (15h). That is,

(23)

(P2) is reformed by,

(P2.1)  (23a)

subject to (23b)

(23c)

(23d)

Thus, the constraints in (23b) and (23d) are defined in terms of

(24)

We can deduce that the ideal α should be as high as feasible by looking at the highest limit of α on the right side in (23c).

(25)

**4.3. Comparing performance with relay processing delay**

Now, considering delay processing, we investigate the optimal covert rate in the DF and AF relay systems. The relationship between the codeword lengths of DF relay and AF relay results in the same processing delay by, according to the author in [1].

(26)

in the high transmit power environment for a delay factor . We can think of two cases for : When = 0, there is no processing delay between the DF and AF relay systems; on the other hand, when , there is a larger processing difference between the DF and AF relay systems. The public and covert rates between DF and AF are correlated with (26)

and (27)

To conduct a delay-aware comparison, we begin by substituting and for and respectively for (P1). Then, the resulting and are multiplied by for scaling purposes.

To maintain the minimum required quality of service for public messages as specified in (19), adjustments to the covert rate in constraint (20b) are necessary, as in [1]

(28)

(29)

respectively. We investigate the optimal covert rate with AF relay in (9) as

(30)

**Chapter 5**

**Numerical Results**

We evaluate and compare the covert communication performance within the relay systems by conducting numerical simulations. The channel coefficient between nodes and for is determined as a function of the distance between them. The nodes are lined up in a straight line, as illustrated in Fig. 5.1.

In [1], we first scale the channel coefficient where denotes the path loss. Here, ​ signifies the path loss at a reference distance , and denotes the path loss exponent. The small-scale channel variable ​ follows a complex normal distribution as seen in Figures 5.2 to 5.7.

**5.1 System Setups**

We analyze the system under the following configurations: bandwidth , the distance between source and relay , relay-to-destination distance , source transmit power , DF and AF relay transmit power , mean noise power at the DF and AF relay, noise uncertainty bound dB, noise power at the destination node , path-loss exponent , minimum quality of service for public and covert messages and respectively, and processing delay factor .

A graph with different colored circles

Description automatically generated with medium confidence

Figure 5.1: Node placements

**5.2 DEP versus Source Transmit Power**

A graph of a function

Description automatically generated

Figure 5.2: Average DEP versus source transmit power with

Fig. 5.2 illustrates the relationship between the detection error probability (DEP) and the source transmit power . When the value of ranges between 0 dBm and 20 dBm, we first see that every scheme's detection error probability (DEP) is high. After that, the DEP falls until reaches 40 dBm, at which point it rises once more in tandem with growth. It is observed that for both the DF and AF relays, the higher bounds of are and , respectively. To get the highest feasible DEP, it is preferred to maximize .

We can also confirm that DF performs better than AF when rises. Additionally, as the processing delay of DF increases in comparison to AF, it results in a smaller .

**5.3 DEP versus Relay Transmit Power**

**A graph of a function

Description automatically generated**

Figure 5.3: Average DEP versus relay transmit power with

Fig.5.3 shows the average DEP for different relay transmit power . It is noticeable that in the beginning region, DF and AF relay DEP perform equivalently, but DF outperforms AF with increasing . Note that in the DF relay has a higher bound of , therefore for maximum DEP.

**5.4 DEP versus Public Rate Threshold**

A graph of a function

Description automatically generated

Figure 5.4: Average DEP versus minimum quality of service for public messages with

Fig. 5.4 presents the average DEP in the actual range of .We observed that DF relay demonstrates higher DEP than AF relay when is low with moderate , but DF and AF relay exhibit the same DEP performance with increasing

It is noteworthy that when is high, AF performs better than a low DF processing delay .

**5.5 DEP versus Covert Rate Threshold**

A graph of a graph with blue and purple lines

Description automatically generated

Figure 5.5: Average DEP versus minimum quality of service for covert messages with

The graph in Figure 5.5 depicts the average DEP corresponding to various .

It is clear from the graph that DEP performance in both the DF and AF relay systems decreases when the minimum quality of covert rate increases; nonetheless, in the end, the DF relay system outperforms the AF relay system. The optimal value is dropping progressively when is gradually going up.

**5.6 DEP versus Processing Delay Factor**

A graph with blue and purple lines

Description automatically generated

Figure 5.6: Average DEP versus processing delay factor

Fig. 5.6 displays the average DEP for different processing delay factor We see that DF outperforms AF, especially for longer DF processing delays, which is the highest result due to the minimum required quality of service for covert message . Additionally, in Figure 5.5, we observed that the longer DF processing delay performs better than the AF relay when increased .

**5.7 DEP versus Noise Uncertainty Bound**

A graph of a number of numbers and lines

Description automatically generated with medium confidence

Figure 5.7: Average DEP versus noise uncertainty bound with

In figure 8, the average DEP is compared to the noise uncertainty bound .   
When increases, the variance of also escalates, which affects the optimal value of in the AF relay system. The overall performance of the DF relay is better than that of the AF relay, as we saw that a longer DF processing delay was given a better outcome result in figures 5.5 and 5.6, respectively, as shown by the same result in this figure 5.7.

**Chapter 6**

**Conclusion**

The goal of this chapter is to wrap up this thesis. We go over the research work's closing remarks in this thesis. We are also prepared for potential further developments of the study that is described in this thesis.

**6.1 Conclusion**

This thesis investigates the comparison of DEP between DF and AF relay systems by taking the decoding processing delay into consideration. We initially gave more focus to the transmission power balancing between the public and covert messages, aiming for maximum DEP in DF and AF relays. Then we analyzed the delay-ware comparison between DF and AF relay systems, utilizing the derived closed-form covert rates. In our analysis, we include various system parameters such as source and relay transmit power, noise uncertainty bound, and minimum required quality of service for both public and covert messages, leading to different performance dynamics between DF and AF. Finally, numerical results are utilized to assess the influence of system parameters on DEP performance.

**6.2 Future Work**

The results of this thesis can provide benefits for multiple antennas in DF, CF, or AF relays.For future study, we propose to evaluate such detection error probability (DEP) scenarios.

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**Abstract**

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Advisor: Jihwan Moon

In this thesis, we find out the maximum detection error probability (DEP) across varying relay system types, specifically decode-and-forward (DF) and amplify-and-forward (AF). In our analysis, we consider a scenario where a transmitter sends both public and covert messages to a receiver through a relay, while the warden attempts to uncover covert messages. Considering the relay’s minimum DEP, we strategically allocate power between the public and covert messages to gain the highest possible DEP. This optimization process involves balancing the transmission power between the public and covert messages, aiming for maximum DEP.

We further analysis a delay-conscious comparison between DF and AF relay systems, utilizing the derived closed-form covert rates. In our analysis, we include various system parameters such as source and relay transmit power, noise uncertainty bound, and minimum required quality of service for both public and covert messages, leading to different performance dynamics between DF and AF. Finally, numerical results are utilized to assess the influence of system parameters on DEP performance.